

Discrete Symmetries/Discrete Theories

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Abstract

Dynamical, metastable supersymmetry breaking appears to be a generic phenomena in supersymmetric field theories. It's simplest implementation is within the so-called “retrofitted O’Raifeartaigh Models”. While seemingly flexible, model building in these theories is significantly constrained. In gauge-mediated versions, if the approximate R symmetry of the theory is spontaneously broken, the messenger scale is fixed; if explicitly broken by retrofitted couplings, a very small dimensionless number is required; if supergravity corrections are responsible for the symmetry breaking, at least two moderately small couplings are required, and there is a large range of possible messenger scales. In gravity mediated versions, achieving $m_{3/2} \approx M_Z$ is a problem of discrete tuning. With plausible assumptions, one can’t achieve this to better than a factor of 100, perhaps accounting for a *little hierarchy* and the surprisingly large value of the Higgs mass.

1 Introduction: The Genericity of Metastable DSB

As Nelson and Seiberg pointed out[1], generic, stable spontaneous supersymmetry breaking requires a continuous R symmetry. If we insist that there should be no exact continuous R symmetries in nature, then we expect that, at some level, any continuous R symmetry should be explicitly broken, leading, generically, to restoration of supersymmetry somewhere in the space of fields. Discrete symmetries, on the other hand, are plausible in generally covariant theories, and indeed frequently arise in string constructions.¹ A simple possibility is that the discrete symmetry is a subgroup of the required continuous R symmetry. This can readily be implemented to generate metastable O’Raifeartaigh models. For example, in a theory with fields X, Y, A transforming, under a Z_N symmetry, as:

$$X \rightarrow \alpha^2 X \quad Y \rightarrow \alpha^2 Y \quad A \rightarrow A \quad (1)$$

with $\alpha = e^{\frac{2\pi i}{N}}$, and also a Z_2 under which A and Y are odd, the superpotential has the structure

$$W = X(A^2 - f) + mAY + \left(\frac{YA^3}{M} + \frac{X^{N+1}}{M^{N-2}} + \dots \right) \quad (2)$$

Ignoring the non-renormalizable couplings, the theory possesses a supersymmetry-breaking ground state at the origin of X, Y . Including these couplings, there is a supersymmetric ground state at large X, Y . The supersymmetry-breaking state is metastable. It exhibits an approximate, continuous R symmetry. This would seem a generic phenomenon.

One would like to understand the breaking of supersymmetry dynamically. Models with stable dynamical supersymmetry breaking (DSB) were discovered some time ago[5]; they seem quite special, and pose challenges for model building. Models of metastable DSB (MDSB) were considered by Intriligator, Shih and Seiberg[6] exhibited strongly coupled models which exhibit metastable dynamical supersymmetry breaking. The ISS class of models are a rich and interesting set of theories, but they pose challenges for building models. An even broader class of theories is obtained by studying the O’Raifeartaigh models, and rendering the scales (f and m) in eqn. 2, for example) dynamical[7, 8, 9]. In these “retrofitted” models, the discrete R symmetry is spontaneously broken by gaugino condensation or its generalizations[9]. This symmetry breaking can also readily generate a μ term. If one retrofits an O’Raifeartaigh model in which all fields have R charge 0 or 2, one has a problem (also typical of ISS models) that the approximate R symmetry is not spontaneously broken. A simple approach, adapted in [9], is to retrofit one of the models of Shih[10], in which not all field have such charges. But given

¹Whether they are “typical”, and might emerge in a landscape context, is another question[2, 3, 4].

the seeming freedom of the retrofitted approach, it is interesting to ask whether one can break the continuous R symmetry explicitly. In particular, if there is a distinct, messenger sector, it would seem possible that retrofitting a breaking of the approximate R symmetry might not spoil supersymmetry breaking. This might allow construction of classes of models of *General Gauge Mediation*[11]. Alternatively, supergravity corrections might dominate, as has been discussed by Kitano[12]. We'll see in this case one can obtain the structure of minimal gauge mediation (MGM).

There is another interesting feature of the retrofitted models, stressed first in [9]. If one assumes that higher dimension operators are controlled by the Planck scale, M_p , then the expectation value of the superpotential, $\langle W \rangle$ is readily of the correct order of magnitude to cancel the cosmological constant. This is remarkable; it means that one neither has to introduce a peculiar, R -breaking constant in the superpotential, nor introduce additional dynamics (e.g. additional gaugino condensates) to account for the observed dark energy (of course, one must still tune an order one constant to incredible accuracy). This is in contrast to the viewpoint, for example, of KKLT[13], that the constant in the superpotential is to be thought of as a random number, selected as part of the anthropic determination of the cosmological constant.

If we insist on this relation, there are striking restrictions on the allowed theories. We will see, in particular, that the underlying scale of supersymmetry breaking (as measured by $m_{3/2}$), sometimes takes on discrete values. In such theories, the usual questions of fine tuning become a question of selection of discrete, rather than continuous, parameters.

In this note after reviewing generalized gaugino condensation in section 2, we briefly revisit the problem of retrofitting gravity mediation, focussing especially on the discrete choices required (particularly in the sector responsible for discrete R symmetry breaking) in section 3. Here the observation concerning the cosmological constant relates the scale of the new interactions to $m_{3/2}$; with some plausible assumptions about unification, this scale is determined, once one makes a (discrete) choice of the underlying gauge group. $m_{3/2}$ is then exponentially dependent on the leading beta function of the underlying theory, and one can ask how closely one can (discretely) tune the gravitino mass to M_Z . We will see that with some plausible assumptions about coupling unification (more precisely, a plausible *model* for coupling unification), one typically misses by factors of order 100, perhaps providing an explanation of a little hierarchy.

We then consider the problem of retrofitting models of gauge mediation in sections 4-6. We will take the observation above about the cosmological constant as a guiding principle. We will

see that this is a significant constraint. All of the models possess an approximate, continuous R symmetry. We will consider the possibilities that this symmetry is spontaneously broken, or explicitly broken. Given the current experimental constraints, we will accept a significant degree of tuning, and take this scale to be large, of order 10^6 GeV. Tuned models of gauge mediation have been considered in [14].

Apart from the fact that one can readily build realistic models, there are several striking features which emerge from these studies.

1. In models with spontaneous breaking of the R symmetry, the scalings are fixed by discrete choices. Quite generally,

$$\sqrt{F} \approx 10^9 \text{ GeV} \tag{3}$$

corresponding to a messenger scale of order 10^{12} GeV (an interesting number, for example, from the perspective of axion physics) and $m_{3/2} = 1$ GeV.

2. In models in which one retrofits an explicit breaking of the R symmetry, small couplings are required in order that the graviton mass be small, and that the gauge-mediated contributions dominate.
3. In models in which the breaking of the R symmetry arises from supergravity corrections (i.e. the low dimension terms in the theory respect the R symmetry), one can obtain acceptable models without exceptionally small dimensionless parameters. The messenger scale can range over a broad range of scales; in the simplest cases, the superparticle spectrum is that of mgm.
4. As has been noted previously[9], a suitable μ term can readily be obtained, though this typically requires the introduction of a small, dimensionless number.
5. As has been discussed elsewhere, if the μ term arises as a result of retrofitting, B_μ is small, so $\tan \beta$ is large[8].
6. With the assumption of a large scale, Λ_{gm} , CP constraints are weakened. In some of the models we will describe, however, CP conservation is automatic.

In section 7, we present our conclusions.

2 Brief Review of Discrete R Symmetries and Generalized Gaugino Condensation

Crucial to most discussions of supersymmetry dynamics is gaugino condensation. Gaugino condensation can be defined, in a general way, as dynamical breaking of a discrete R symmetry, accompanied by dimensional transmutation. As such, it occurs in a wider variety of theories than just pure (supersymmetric) gauge theories. For example, an $SU(N)$ gauge theory with N_f flavors, and a singlet, S , with superpotential

$$W = y_f S \bar{Q}_f Q_f + \frac{\gamma}{3} S^3 \quad (4)$$

has a Z_{3N-N_f} R symmetry. This is broken by $\langle \lambda\lambda \rangle \sim 32\pi^2 \Lambda^3$, and by $\langle S \rangle$. In the limit $|\gamma| \ll |y_f|$, S is large, and one can integrate out the quark fields, obtaining an effective superpotential:

$$W = N \left(\prod y_f \right)^{1/N} S^{N_f/N} \Lambda^{3-N_f/N} + \frac{\gamma}{3} S^3. \quad (5)$$

This has supersymmetric stationary points with

$$S \sim \Lambda \left[\left(\prod y_f \right)^{\frac{1}{N}} \frac{N_f}{\gamma} \right]^{\frac{N}{3N-N_f}} \quad (6)$$

(this model also has a disconnected, runaway branch; this can be avoided, if desired, by adding additional scalars). The low energy superpotential has a constant term,

$$W_0 = \left\langle -\frac{1}{4g^2} W_\alpha^2 \right\rangle \sim N \Lambda^3 \quad (7)$$

With these ingredients we can readily “retrofit” any O’Raifeartaigh model. For example, we can take

$$W = X(A^2 - \mu^2) + mAY \quad (8)$$

and replace it by

$$W = X(A^2 - c \frac{W_\alpha^2}{M_p}) + \kappa S A Y. \quad (9)$$

This model has a metastable minimum near the origin, as seen from the standard Coleman-Weinberg calculation. It has a runaway to a supersymmetric vacuum at ∞ , separated by a barrier from the (metastable) minimum at the origin. Under the discrete R , X is neutral, while A transforms like the gauginos, S has charge $2/3$, and Y charge $1/3$. Various higher dimension terms are allowed, which lead to (faraway) supersymmetric vacua.

Clearly any dimensional coupling can be generated in this way, and the possibilities for model building are vast. This type of construction will be the basic ingredient of all of the models of this paper. One striking feature of this model is that, for c an order 1 constant, the cosmological constant can be very small; upon coupling to supergravity, the terms $|\frac{\partial W}{\partial X}|^2$ and $-\frac{3}{M_p^2}|W|^2$ are automatically of the same order of magnitude. We view this remarkable coincidence as a potential clue, and will largely insist that it hold in the models we describe in this paper. This will greatly restrict possibilities for model building.

3 Retrofitted Gravity Mediation: Discrete Choices

In gravity mediated models, we can make do with less structure than the O’Raifeartaigh models; higher order supergravity and Kahler potential corrections can stabilize X , without additional fields like A . With

$$W = -\frac{1}{4}W_\alpha^2(g^{-2} + cX) \tag{10}$$

we have a Polonyi-type model. If we simply define $X = 0$ as the location of the minimum of the potential, we can expand the Kahler potential about this point, and impose the conditions of a stable minimum at a the origin with (nearly) vanishing V [15]. Note, in particular, that X is neutral under the R symmetry, so the origin is not a distinguished point.

If we take the gravitino mass to be of order 10 TeV, we expect stop masses of this order, and can really account for the apparent observed Higgs mass. But such a choice leaves several questions.

1. Raising the scale ameliorates, but does not resolve, the problems of flavor of supergravity models. This has lead to the suggestion, in [16], that the scale of supersymmetry breaking should be much higher, even 1000’s of TeV. Alternatively, one might invoke some model for flavor, e.g. those of [17]. (Other aspects of these question are under study[18]. For 10 TeV squarks, such models are easily compatible with existing data on flavor-changing processes.
2. 10 TeV represents a significant tuning. Even allowing, say, anthropic selection among approximately supersymmetric states in a landscape, where might such a little hierarchy come from? In this subsection, we will offer a possibility. Others have been suggested in [19, 20].

3. Are there observable consequences of such a picture? The authors of [16] invoke unification and dark matter to argue that some gauginos should be relatively light. In [15], however, the genericity of light gauginos was questioned.

Once one has allowed for the possibility that there may be some degree of tuning, the question which immediately follows is: how much tuning is reasonable. A part in $10^3 - 10^4$? This would lead to squarks in the $3 - 10$ TeV range. A part in $10^6 - 10^7$? This would allow squarks in the $10^3 - 10^4$ TeV range. Here we suggest one possible origin for tuning, which points towards the former.

Suppose, for the moment, that we take the R breaking sector to be a pure gauge theory, and we require vanishing of the cosmological constant. Then we have, as parameters, the choice of gauge group, the value of the gauge coupling at some fixed large scale, and a small number of order one terms in the Kahler potential. Up to order one numbers, the choice of gauge group and the value of the coupling fix $m_{3/2}$. We can ask whether we can achieve, among possible groups, $m_{3/2} \approx M_Z$. To make sense of this question, we need to make further assumptions. We will assume that *all* of the gauge couplings unify at M_p , and employ the standard results for unification within the MSSM. Then, given a choice of gauge group in the R breaking sector, the scale of that sector, *and the value of the gravitino mass*, $m_{3/2}$, are determined. Confining our attention, for simplicity, to $SU(N)$ theories, we have that

$$\Lambda = M_p e^{-\frac{1}{b_0} \frac{8\pi^2}{g^2(M_p)}} \quad (11)$$

and

$$m_{3/2} = \frac{N\Lambda^3}{M_p^2} \quad (12)$$

For N such that $b_0 = 3N$ gives a gravitino mass in the TeV range, a change in N by 1 results in a change in the gravitino mass of order 10^4 . So, accounting for threshold and other effects, one would expect, typically, to have a graviton mass of order 100 times M_Z (or .01 M_Z). This might well account for the sort of tuning needed to account for the Higgs mass, and not much more! This is, of course, just one possible model; other models might make significantly different predictions.

4 Retrofitting Gauge Mediation: Spontaneous (Continuous) R Symmetry Breaking

In broad classes of O’Raifeartaigh models, one finds that the (continuous) R symmetry is unbroken at the minimum of the potential when one performs the requisite Coleman-Weinberg calculation. In retrofitting such models, and in building gauge-mediated theories, we need to explicitly break the symmetry, or to insure that there is no such symmetry in the messenger sector. Instead, in this section, we consider retrofitting in models in which the R symmetry is spontaneously broken. The simplest such model has superpotential[10]:

$$W = X(\phi_1\phi_{-1} - f) + m_1\phi_1\phi_1 + m_2\phi_{-3}\phi_1 \quad (13)$$

We have not explicitly indicated dimensionless couplings. This model has a metastable minimum at $X \sim m_1, m_2$, provided

$$|f| < |m_1 m_2| \quad (14)$$

When this bound is not satisfied, the model exhibits runaway behavior. When it is, $F_X = f$ is the order parameter for supersymmetry breaking.

Given these remarks, and the constraint of the cosmological constant, the only possibilities for retrofitting are

1. Comparable m_1, m_2 :

$$f \rightarrow \frac{W_\alpha^2}{M_p}, \frac{S^3}{M_p}; \quad m_1, m_2 \rightarrow S \quad (15)$$

with coefficients of order one.

2. Hierarchy of m_1, m_2 :

$$f \rightarrow \frac{W_\alpha^2}{M_p}, \frac{S^3}{M_p}; \quad m_1 \sim S, \quad m_2 \sim \frac{S^2}{M_p} \quad (16)$$

or

$$f \rightarrow \frac{W_\alpha^2}{M_p}, \frac{S^3}{M_p}; \quad m_1 \sim \frac{S^2}{M_p}, \quad m_2 \sim S \quad (17)$$

with suitable order one constants, in each case, so that eqn. 14 is satisfied.

The latter case, however, is problematic if there are no very small dimensionless numbers. First, unless $m_1 \gg m_2$, the R symmetry is unbroken[10]. Following the analysis of [10], if this condition is satisfied, the vev of X is:

$$|\langle X \rangle|^2 \approx \frac{m_1^2}{9\lambda^2} \sim \Lambda^2. \quad (18)$$

if the couplings in the superpotential are of order one. So the scalar component of X is of order Λ (up to dimensionless constants), as in the previous case.

4.1 Couplings to Messengers

In the first case, if we couple X to messengers, with coupling

$$X \widetilde{M} M \quad (19)$$

we have the usual sorts of gauge-mediated relations, but with scales that are now, essentially, fixed. In particular, the scale that sets the masses of squarks, leptons and gauginos is:

$$\Lambda_{gm} = \frac{F_X}{X} = \frac{\Lambda^2}{M_p} \quad (20)$$

(up to dimensionless coupling constants). Requiring

$$\Lambda_{gm} = 10^6 \text{ GeV} \quad (21)$$

(consistent with current experimental constraints, but, needless to say, demanding significant tuning) gives

$$\Lambda = 10^{12} \text{ GeV}; \quad m_{3/2} \sim 1 \text{ GeV}. \quad (22)$$

The scales here are close to those considered in [14], who have discussed some of the issues associated with possible detection and dark matter. These will be further considered elsewhere, but it should be noted that the lightest of the new supersymmetric particles are in the TeV range, and these do not carry color, so their discovery will be challenging, if these ideas are correct.

4.2 The R Axion

Models of this type, where the approximate R symmetry is spontaneously broken, possess an R axion. To determine its mass, we must examine sources of R symmetry breaking. These

will arise from higher dimension terms in the superpotential, and also from coupling the low dimension terms to supergravity. These latter are always present, so we content ourselves with estimating these.

As in the estimate of Bagger, Poppitz and Randall[?], the R breaking arises from terms such as $-3|W|^2$ in the potential. For the retrofitted versions of Shih’s model, writing

$$X \approx \langle X \rangle e^{ia/\langle X \rangle} \quad (23)$$

yields a mass of order

$$m_a^2 \approx m_{3/2}^2 \frac{f}{X} \quad (24)$$

or about 1 TeV, in the present case. This is heavy enough so as not to be astrophysically problematic, and, of course, is difficult to see in accelerator experiments.

4.3 Discrete Tunings

In the gravity mediated case, we saw that, with a model for unification of couplings, discrete changes of theory lead to large changes in $m_{3/2}$. This arose, in part, because we assumed the simplest possibility for gaugino condensation: a gauge theory without matter fields. In the gauge-mediated case, we require a theory with matter, and, while this may represent an increase in complication, smaller steps in the beta function (one instead of three for the pure gauge case) are inherent to this class of models. As a result, the difficulties of tuning do not appear to be as pronounced as in the gravity mediated case we described earlier. A “natural” model of gauge mediation would have

$$\Lambda_{gm} \sim \Lambda_{gm}^{natural} \equiv 4 \times 10^4 \text{GeV}. \quad (25)$$

If we take the R -breaking sector to be an $SU(N)$ gauge theory with N_f flavors and no particularly small dimensional parameters and makes the same unification assumptions we made in the gravity-mediated case, it is easy to choose the number of flavors and colors, so as to obtain Λ_{gm} within a factor of three of $\Lambda_{gm}^{natural}$. So if nature is gauge mediated, understanding the little hierarchy will require additional elements. For example, if there is an underlying landscape, and N and N_f are not uniformly distributed, one might easily account for a hierarchy of several orders of magnitude.

5 Retrofitted Gauge Mediation: Explicit R Symmetry Breaking

Given the seemingly unlimited ability to introduce scales through retrofitting, one is led to consider models in which the O’Raifeartaigh sector has an approximate, unbroken continuous R symmetry, while the would-be R symmetry of the messenger sector is broken by explicit mass terms or couplings in the superpotential. This would be interesting in itself, but especially because, even with the simplest messenger structure, the spectrum would be that of general gauge mediation (as opposed to MGM). But, as we will see in this section, this possibility is remarkably constrained. It is difficult to construct realistic models, without very small dimensionless parameters, subject to the following rules:

1. M_p sets the overall energy scale of the theory.
2. The cosmological constant should vanish at the level of the dynamics responsible for supersymmetry breaking.

A simple model illustrates the main issue. We consider a retrofitted O’Raifeartaigh model with a field, X , neutral under the R symmetry and with F -component Λ^3/M_p . For the coupling to the messengers we take

$$\left(yX \frac{S^m}{M_p^m} + \lambda \frac{S^m}{M_p^{m-1}} \right) \widetilde{M} M \quad (26)$$

The problem is that, for any choice of m ,

$$m_{3/2} \approx \frac{\lambda}{y} \Lambda_{gm} \quad (27)$$

If $\Lambda_{gm} \approx 10^6$ GeV, it is necessary that $\frac{\lambda}{y}$ be quite small if the gauge-mediated contributions are to dominate.

The difficulty here arises because X is invariant under the symmetry. One might try to avoid this by considering a different type of O’Raifeartaigh model, in which $|f| \gg |m|^2$. For example,

$$W = X \left(\frac{S^{2m}}{M_p^{2m-2}} - A^2 \right) + \frac{S^n}{M_p^{n-1}} AY. \quad (28)$$

If $m < n$, A acquires a vev, and

$$F_Y \approx \frac{S^{m+n}}{M_p^{m+n-2}}. \quad (29)$$

Requiring vanishing of the cosmological constant gives

$$m + n = 3. \quad (30)$$

So there are a limited set of possibilities; indeed, we need $n = 2, m = 1$. But if the fields S transform with $\alpha^{2/3}$ under discrete R -symmetry, then Y is again neutral, and we encounter exactly the difficulty of the previous model.

Given these difficulties, one might try to construct a model in which X transforms non-trivially under the R symmetry. In a model like

$$W = y_f \frac{S^k}{M_p^{k-1}} \tilde{Q}_f Q_f - \frac{\gamma}{p} \frac{S^p}{M_p^{p-3}} \quad (31)$$

S transforms as $\alpha^{2/p}$. But now if we are to replicate our “cosmological constant coincidence”, we require that X couple to $\frac{S^p}{M_p^{p-4}}$. But then X is neutral again.

There are other strategies one might try, but it seems difficult, in general, to break the R symmetry subject to our rules. Needless to say, relaxing these would open up additional possibilities.

6 Explicit R Breaking By Supergravity

Finally, one might wonder whether simply coupling one of these systems to supergravity might provide an adequate breaking of the continuous R symmetry².

In the simplest OR model, coupled to messengers:

$$W = Xf + \lambda X A^2 + mAY + c f M_p |\gamma X M \bar{M}|. \quad (32)$$

(with c an $\mathcal{O}(1)$ constant), the tadpole (linear term in the potential) for X is of order

$$\Gamma \approx \frac{f^2}{M_p}. \quad m_X^2 = \frac{\lambda^4 f^2}{16\pi^2 m^2}. \quad (33)$$

So, if $f \sim \frac{\Lambda^3}{M_p}$ and $m \sim \Lambda$,

$$X \approx \frac{\Gamma}{m_X^2} \sim \frac{\Lambda^2}{M_p} \left(\frac{\lambda^4}{16\pi^2} \right)^{-1} \quad (34)$$

²Supergravity corrections of this type in gauge mediation have been considered by Kitano[12].

The simplest coupling to messengers again has the MGM form:

$$\gamma X M \bar{M} \quad (35)$$

There are now two conditions on γ and λ . First, we require that the messenger masses not be tachyonic:

$$|\gamma X| > |F_X| \quad (36)$$

and second that the corrections to the X potential due to the messengers be small compared to those from the X interactions with the massive field A :

$$\frac{\gamma^2}{X^2} \ll \frac{\lambda^4}{m^2}. \quad (37)$$

These conditions require that both λ and γ be small, but they do not have to be *extremely* small. For example, they are satisfied with

$$\lambda = 0.08; \quad \gamma = 0.01; \quad \gamma X \approx 10^{12} \text{ GeV}. \quad (38)$$

A slightly smaller λ yields X at the maximum scale for gauge mediation, while allowing a larger γ :

$$\lambda = .05; \quad \gamma = 0.10; \quad \gamma X \approx 10^{15} \text{ GeV}. \quad (39)$$

On the other hand, once λ is larger than about 0.18, γ becomes non-perturbatively large.

So overall, one can achieve a realistic model in this manner, with λ and γ which are small but not extremely so. The gauge mediated scale can range over the full range normally considered for gauge mediated models; the simplest models have the spectrum of MGM.

7 Conclusions

It seems likely that our cherished ideas about naturalness and supersymmetry are not correct. Supersymmetry, if present at low energies, appears somewhat tuned and may be hard, or impossible, to find. The apparent value of the Higgs mass suggests that the supersymmetry breaking scale might be in the 10 – 100 TeV range.

In this paper, we have reexamined the question of dynamical supersymmetry breaking in the framework of retrofitted models. These models appear to have a rather generic character, and allow one to address easily questions ranging from the μ term to the cosmological constant.

With plausible assumptions, they are highly constrained. We have considered gravity mediated models (extending slightly the work of [15]) and gauge mediated models. In both cases, the requirement of small cosmological constant strongly constrains the underlying theory. In the supergravity case, the question of fine tuning, i.e. of how close $m_{3/2}$ lies to M_Z , is a question of discrete choices. With plausible assumptions about the microscopic theory, the apparent degree of tuning is typically a part in thousands or tens of thousands, perhaps explaining the tuning we see. It is still necessary, in this case, that there be some suppression of low energy flavor violation. Models along the lines of [17] which achieve this will be considered elsewhere.

Our principle focus, however, was on gauge mediated models. We constrained our constructions, again, by requiring the possibility of small cosmological constant in the effective theory, and a fixed supersymmetry breaking scale (corresponding to stops at 10 TeV, or $\Lambda_{gm} = 10^6$ GeV). We explored the question of whether one might break the approximate, continuous R symmetry explicitly, taking advantage of the freedom apparently implied by the retrofitted constructions. While we cannot claim that our survey of possible constructions are complete, in broad classes of theories:

1. If the R symmetry is spontaneously broken, and absent very small dimensionless couplings, the underlying scale of supersymmetry breaking is fixed, with a gravitino mass of order 1 GeV.
2. If the R symmetry is explicitly broken through retrofitted couplings in the superpotential, a very small dimensionless number, of order 10^{-6} , is required in order that the gauge-mediated contributions dominate.
3. If the R symmetry is explicitly broken by supergravity effects, two small, but not exceptionally small couplings, are required. The has scale of the messengers ranges, in simple cases, from 10^7 to 10^{15} GeV.

We draw from these observations the conclusions:

1. If supersymmetry breaking is gravity mediated, the relatively high scale may result from the limited effectiveness of required discrete tuning. Flavor symmetries, associated with quark and lepton masses, readily can provide adequate alignment of soft breakings to suppress low energy flavor changing processes[5].
2. If supersymmetry breaking is gauge mediated, the approximate R symmetry may be spontaneously broken, in which case the underlying scale of supersymmetry breaking

corresponds to a gravitino mass of order 1 GeV, and the mass of the corresponding R axion is similar. Simple models of Minimal Gauge Mediation can be realized in this framework.

3. The breaking may be explicit. In the most compelling models, the breaking of the R symmetry arises from supergravity effects. The messenger scale may be small or large, and again MGM can be realized.

There remains the most important question: is there anything one might hope to see[14]. In a subsequent publication, we will focus on this issue, considering questions such as dark matter and its implications for possible light states, electric dipole moments, and rare processes.

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